Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 5078–5083, May 1996
Ecology

Why fisheries collapse and what to do about it

JONATHAN ROUGHGARDEN* AND FRASER SMITH†‡

[a]Department of Biological Sciences and Department of Geophysics and [b]Department of Biological Sciences and Center for Conservation Biology, Stanford University, Stanford, CA 94305

Communicated by Donald Kennedy, Stanford University, Stanford, CA, December 8, 1995 (received for review August 15, 1995)

ABSTRACT **With the collapse of fisheries in many parts of the world causing widespread economic harm, attention is focused on a possible cause and remedy of fishery collapse. Economic theory for managing a renewable resource, such as a fishery, leads to an ecologically unstable equilibrium as difficult to maintain as balancing a marble on top of a dome. A fishery should be managed for ecological stability instead—in the analogy, as easy to maintain as keeping a marble near the base of a bowl. The goal of ecological stability is achieved if the target stock is above that producing maximum sustainable yield and harvested at less than the maximum sustainable yield. The cost of managing for ecological stability, termed "natural insurance," is low if the fishery is sufficiently productive. This cost is shown to pay for itself over the long term in a variable and uncertain environment. An ecologically stable target stock may be attained either with annually variable quotas following current practice or, preferably, through a market mechanism whereby fish are taxed at dockside if caught when the stock was below target and are untaxed otherwise. In this regulatory environment, the goal of maximizing short-term revenue coincides with the goal of ecological stability, thereby also maximizing long-term revenue. This new approach to fishery management is illustrated with the recently collapsed Newfoundland fishing industry. The Newfoundland cod fishery is expected to rebuild to an ecologically stable level in about 9 years and thereafter support an annual harvest of about 75% of the 1981–1990 average.**

In October 1994, the Georges Bank fishery was closed to the fishing of cod, haddock, and yellowtail flounder by the New England Fishery Management Council [New York Times, Oct. 27, 1994]. This action followed a similar closure of the Grand Bank fishery off Newfoundland to selected groundfish species in 1993 (1).[d] These closures are not isolated administrative actions. They reflect a worldwide condition of overfishing (2).

In 1973, the Canadian Department of Fisheries and Oceans instituted annual quotas—total allowable catches (TACs)—on the fishing of cod off Newfoundland in an effort to prevent overexploitation. As Fig. 1 shows, Newfoundland's cod fishers obeyed the law and did not exceed the TACs, yet the fishery still collapsed.

Many causes have been cited for this collapse, including a lack of political will to impose adequate quotas, overoptimistic stock assessments by fishery scientists, poaching from foreign fleets, exceptional mortality from natural predators, climate change, subsidies to fishers, and overcapitalization following the imposition of the 200-mile limit (1, 3). We do not take a position on the relative importance of these causes. We offer instead a reexamination of management targets and emphasize the economic value of ecological stability.

Problem

Fig. 2 depicts a fishery's production dN/dt as a hump-shaped function of stock size N. The slope of this curve at $N = 0$ is the

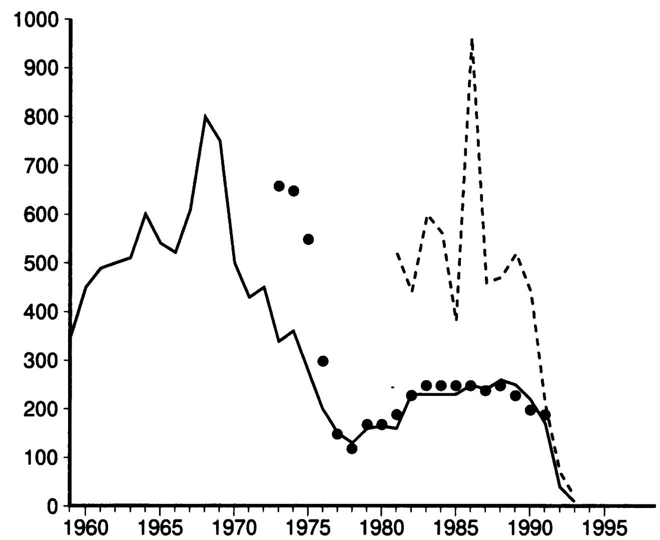

FIG. 1. History of Newfoundland cod fishery (divisions 2J, 3K, and 3L). Annual harvest in thousands of tons is plotted as a solid line, stock size is plotted as a dashed line, and annual quotas are plotted as solid dots. Fishery shows three phases—1960–1980, 1981–1990, and 1991–1993. Harvest was highest in the first phase, lower in the second phase, and in the third phase the fishery collapsed.

intrinsic rate of increase r (0.25 in the example) and an unharvested stock comes to equilibrium at K, the carrying capacity (1000 in the example—Fig. 3 illustrates the entire curve).[e] The curve peaks at $K/2$, the stock size that produces the maximum sustainable yield (MSY).

In natural resource economics, the problem of determining an optimal harvest rate is viewed as a problem in allocating capital between natural and financial stocks. The optimal harvest rate takes place at the target stock where the slope of the production function, $F'(N)$, equals the savings account interest rate, ρ (0.05 in the example).[f] At this target stock, the marginal return from investing in natural stock (fish) equals the marginal return from investing in financial stock (savings).[g] Thus, in Fig. 2, management for maximum revenue is to

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Abbreviations: TAC, total allowable catch; MSY, maximum sustainable yields.

[c]Present address: Decision Focus, Inc., 650 Castro Street, Suite 300, Mountain View, CA 94041.

[d]These actions are drastic, like reporting that Nebraska could no longer grow corn, or Kansas wheat, until farmers wait 10 years for the soil to regenerate.

[e]A standard model for a renewable resource such as a fishery is the logistic equation $dN/dt = rN(K - N)/K = F(N)$. The hump-shaped curve of Fig. 2 is the right-hand side of this equation. The per capita growth of fish $(dN/dt)/N$, is a decreasing function of N because the fish are competing with one another for such resources as food and space. The overall dynamics of the stock, including both production and harvest at rate h, is $dN/dt = F(N) - h$.

[f]The optimal equilibrium solution is the pair (N_o, h_o) where the optimal stock size N_o is the root of $F'(N_o) = \rho$ and the optimal harvest h_o is the production at the optimal stock size $h_o = F(N_o)$. For the logistic model, $N_o = (K/2)(1 - \rho/r)$ and $h_o = rK(1 - (\rho/r)^2)/4$.

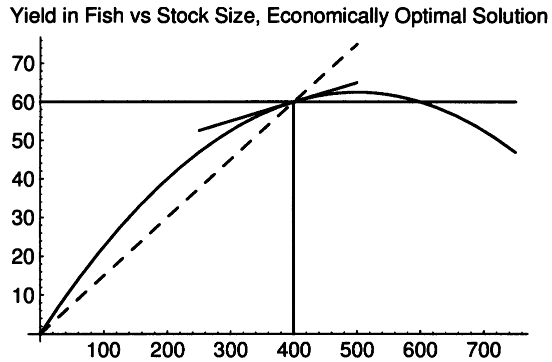

FIG. 2. Economically optimal stock size is 400, which yields an optimal yearly harvest of 60. At this configuration the slope of the fishery production curve equals the interest rate, as required by economic theory. But the stock size of 400 is an ecologically unstable equilibrium. The stable stock sizes for a harvest of 60 per year are 600 and 0. If the stock is regulated through graded control, the optimal fishing mortality is the slope of the diagonal dashed line, which is 0.15. (Figs. 2–5 use $r = 0.25$ per annum and $K = 1000$ individuals in the logistic equation, and $\rho = 0.05$ per annum as the interest rate.)

establish a target stock of 400 fish and thereafter to harvest 60 fish per unit time.

The problem is that this point of optimal harvest is an ecologically unstable equilibrium under constant harvest. If the harvest continues at the optimal rate (60 in the example) and if environmental fluctuations drive the stock size slightly below 400, then the harvest exceeds the production and the stock is driven further toward extinction. Conversely, if the stock fluctuates above 400, then the harvest is less than the production and the stock grows. In reality, if stocks are seen to grow, then quotas are usually increased, eventually resulting in a quota that exceeds production and extinguishes the stock.[h] Thus, maintaining the stock at the optimal size of 400 is like balancing a marble on top of a dome.

The observation that a target stock to the left of the hump is unstable under constant harvest has been noted before in the fishery literature (cf. ref. 4), but its relation to natural resource economic theory has been little remarked. The economic and fishery literatures offer different perspectives on how to regulate the stock at this unstable target.

Economic theory views the harvest rate as a control variable in optimal control theory—a quantity under continuing human

[g]Intuitively, imagine investing dollars, one by one, into a savings account or into the fishery. If $r > \rho$, the first dollar would earn more from the fishery than from the savings and should therefore be invested in the fishery. Then consider the next dollar and the next, until the point at which the return from the fishery equals the interest rate. Beyond this point, any additional capital should be invested in the savings account.

[h]An equilibrium stock lies at any point where the horizontal line representing the harvest intersects the hump-shaped curve—that is, a stock size N such that $F(N) = h$. An equilibrium stock to the left of the hump is unstable, and that to the right is stable. Because the interest rate is positive, the economically optimum target is toward the left of the hump because that is where the slope of the production is positive. [A qualification is that the economically optimal target may lie to the right of the hump if the net price of fish depends on stock size, as it does if operating costs depend on stock size. Specifically, if the price per fish is $P(1 - c/N)$, where P is the market price per fish, and c is the coefficient relating costs to stock size, then $c = E/(Pq)$ where E is the price per unit effort, and q is the catchability. With this notation, the economically optimal target stock $N_o = (A + \sqrt{B + A^2})/4$, where $A = c + K(1 - x)$, $B = 8cKx$, and $x = \rho/r$. As $c \to 0$, $N_o \to (K/2)(1 - \rho/r)$. The c must exceed $K/(2 + r/\rho)$ for N_o to lie to the right of the hump. As noted later, the cost coefficient for Newfoundland cod is nowhere near this high. Thus, in the absence of a strong dependence of cost per fish on stock size, the economically optimal target is to the left of the hump and is therefore unstable.]

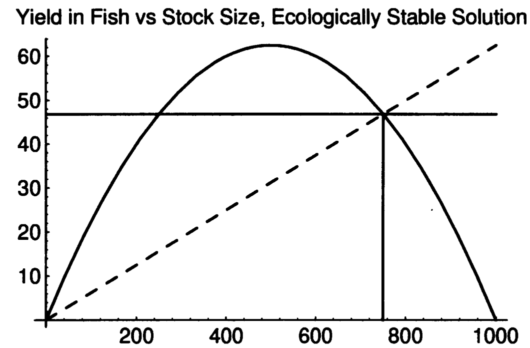

FIG. 3. Ecologically recommended stock size is 750, which supports an annual harvest of 46.9 per year. The stock size is stable and the domain of attraction extends from 250 to 1000. If the stock is further regulated with graded control, the recommended fishing mortality is the slope of the diagonal dashed line, which is 0.06.

control like the volume on a radio. In optimal control theory, an optimal solution consists of both the target equilibrium and a path to that equilibrium. The optimal path to the optimal target is to switch off fishing when the stock is below target, to fish intensively when the stock is above target so that the stock is restored to target as quickly as possible, and to fish at the optimum rate when the stock is on target (cf. refs. 5 and 6). If this so-called bang-bang control could be implemented, then the fishery would be operated in the theoretically most profitable way and it would also be stable. To achieve bang-bang control, management's policy mechanisms must act quickly and accurately.

Fishery theory typically takes the control as graded, not bang-bang, and assumes that harvest is directly proportional to the stock size. From the standpoint of control theory, this control is suboptimal. Fishing is allowed to continue at a reduced rate when it should be stopped altogether because the stock is too low and fishing is not allowed to consume excess stock quickly enough when the stock is too high. A graded control, termed managing for constant effort, may nonetheless be most viable politically. In fishery theory, the constant of proportionality relating stock size to harvest is called the fishing mortality, which itself is viewed as a product of fishing effort and the catchability coefficient. Like bang-bang control, this graded control will stabilize the stock at its target value, provided it can be satisfactorily implemented.[i] In principle, a target fishing mortality is determined as the slope of the line extending from the origin to the target stock, illustrated as a dashed diagonal line in Fig. 1. Then, if the catchability coefficient is known the number of boats that will establish this target fishing mortality is computed and used in principle to set the number of licenses.[j]

Fishery practice does not accord with fishery theory. The catchability coefficient varies with season, year, technology, target species, fishing gear, and nationality (cf. ref. 9, pp. 106–112 and 193), so that annual catch quotas are used in place of regulated effort. In principle, the annual catch quota equals the product of the target fishing mortality, the stock size, and

[i]If the harvest is decomposed into fishing mortality times stock, the dynamics of the stock are $dN/dt = rN(K - N)/K - FN$, where F is the fishing mortality. Furthermore, $F = qE$ where q is the catchability coefficient and E is the fishing effort. The fishing mortality that yields the economically optimal target stock is $F_o = (r + \rho)/2$; this is the slope of a line from the origin to the optimal stock N_o. With this control, N_o is a stable equilibrium. If q is known, the number of boats, E, that bring about F_o is then $E_o = F_o/q$.

[j]Fishery theory also has considered mixtures of bang-bang and graded control. In the fishery literature, a stock size at which harvesting switches off is called an escapement. A combination of escapement and graded control is used by the International Whaling Commission (cf. refs. 7 and 8).

the length of the fishing season, although more complex calculations are necessary to take age structure into account. Fishery biologists believe that annually revised catch quotas are equivalent to constant effort and claim that two-thirds of North American fishery resources are regulated for constant fishing mortality rate (10). As May *et al.* (ref. 11, p. 240) write, "... in practice 'constant quota' strategies are continually reappraised, so that they are not in fact very different from constant effort strategies." This assertion requires that the policy mechanisms used by management to control the stock act quickly and accurately. Yet the quality of data used to determine catch quotas has been criticized repeatedly for inaccuracy and for referring to a census taken a year earlier than the year whose quotas are being managed (12). Furthermore, the environment exhibits interannual variation so that the hump-shaped production curve wobbles around from year to year, with both r and K high in good years and both low in bad years. All in all, managing a fishery for the economically optimal target stock is worse than keeping a marble on top of a dome—it is, in fact, like keeping a marble on top of a dome fastened to the deck of a rolling ship seen through salt-sprayed goggles.

Solution

Fishery management has been studied mathematically for >50 years, during which time May *et al.* (11) concluded that "What seems really needed is not further mathematical refinement, but rather robustly self-correcting strategies that can operate with only fuzzy knowledge about stock levels and recruitment curves." In this spirit, we offer a recommendation: Let the target stock lie to the right of the hump. In general, we recommend a target of $(3/4)K$, which is midway between the hump at $K/2$ and the unharvested equilibrium at K. This target is ecologically stable under constant harvest, and maintaining the stock at this target is like keeping a marble near the base of a bowl (which is possible even on a rolling ship). Fig. 3 illustrates a stock at $(3/4)K$, which in the example sustains a steady state harvest of ≈47 fish per unit time. The stock could fluctuate down to 250 or up to 1000 and still the fishery would return naturally to the value of 750 even in the presence of continued harvesting at 47 fish per unit time. The target of 750 is stable under constant harvest and even more so if managed for constant effort along the diagonal dashed line in Fig. 3.[k]

The economic value of maintaining a stock to the right of the point of maximum sustainable yield may be overlooked because short-term economic incentives favor lowering the stock if it should ever become this high. If the stock is above the level producing the maximum sustainable yield, then adding another fish to the stock lowers the total productivity, whereas removing a fish leads to higher total productivity. Indeed, "thinning" improves the stock's productivity in the short term by diminishing density dependence. Maintaining the stock beyond the point of maximum sustainable yield makes economic sense only when stability is considered.

Cost

Managing a fishery for stability comes at a cost. This cost is the difference between the earnings at the economically optimal equilibrium and the earnings at the ecologically recommended equilibrium. Specifically, the cost of this "natural insurance" is the interest earnings foregone by not investing the difference in stock between the ecological recommendation and the economic optimum (750 − 400 in the numerical example) plus the reduction in annual harvest at the ecological recommendation compared with the economic optimum (60 − 47 in the example). This natural insurance ensures against accidental liquidation of the stock by overfishing.

The cost of natural insurance can be expressed as a fraction of the capital value of the fishery when operated at the economic optimum. The cost depends on the ratio of the interest rate ρ to the intrinsic rate of increase of the fish population, r.[l] If $r > 4\rho$, then the fishery is productive enough to support natural insurance. The fractional cost decreases as fishery productivity increases. When r is 10 times ρ, for example, the cost is ≈2% of the capital value of the fishery. This insurance cost is intermediate between the cost of fire insurance on a house (≈0.1% of the value) and the cost of collision insurance on a car (≈10% of the value). If r is between ρ and 4ρ, the earnings from liquidating the stable fishery (i.e., banking the revenue from harvesting the 750 fish) exceed the earnings from the sustainable harvest that 750 fish support. In this case, the fishery is not productive enough to pay for insurance and instead should be operated at the economic optimum as long as possible. If $r < \rho$, the resource should be treated as depletable.

Benefit

Is natural insurance worth buying? The answer depends on how great is the risk of fishery collapse. To assess the value of natural insurance, we simulate the economic return from a fishery for several magnitudes of risk. The simulation views the fishery as though it were a mutual fund, started with $1000 with each fish assumed to be worth $1. The portfolio consists of two investments: a fish stock with an average r of 1 and an average K of 1000, and a savings account whose annual interest rate is 5%. The return on the portfolio over 50 years is computed as a function of the allocation of the initial investment between (fish and savings.[m] For example, if a target stock of 250 is chosen, the remaining $750 is invested into savings. Each year the portfolio's value is updated. At the beginning of each year a total allowable catch is computed based on the estimated stock of the prior year, and this catch is then taken during the year. The proceeds from the harvest are deposited in the savings account. The savings account accrues interest during the year. So the portfolio as a whole gains in value from fishing plus interest on savings. All the risk is in the fishery component of the portfolio. The fishery incurs three sources of random variation each year: first, the environment varies, resulting in

[k]The recommended stock $N_r = (3/4)K$ leads to a sustainable harvest in the logistic model of $h_r = 3rK/16$. The fishing mortality that accomplishes this harvest is $F_r = r/4$. A stock of $(3/4)K$ is recommended because the stable domain of attraction surrounding this stock size is large and the harvest is ample. Other target stock sizes could be chosen provided they are to the right of the hump. The closer the target is to $K/2$, the smaller the stable domain of attraction and the larger the harvest. The nearer the target is to K, the larger the stable domain of attraction but the smaller the harvest. To compare measures of stability, the eigenvalue at equilibrium for a target stock of N is $\lambda_h = r(1 - 2N/K)$ with constant harvest, and $\lambda_F = -rN/K$ with constant effort. λ_h is negative if $N > K/2$ and λ_F is negative for all positive N. Both eigenvalues become more negative as $N \rightarrow K$, indicating that greater stability is attained at progressively higher target stocks. $\lambda_F < \lambda_h$, indicating that managing with constant effort is always more stable than managing for constant harvest, although the difference between these approaches tends to 0 as the target approaches K—that is, the relative advantage of managing for constant effort instead of constant harvest disappears as the target approaches the carrying capacity.

[l]Natural insurance is feasible if $h_r > \rho N_r$, which reduces to $r > 4\rho$. The cost of natural insurance is $\rho(N_r - N_o) + (h_o - h_r)$ and the capital value of the fishery is h_o/ρ—i.e., the capital needed to produce interest equal to the optimum yield from the fishery. Therefore, the cost as a fraction of the capital value of the fishery is $(\rho(N_r - N_o) + (h_o - h_r))/(h_o/\rho)$, which works out to be $\rho((1 + 2x)^2)/(4(1 - x)^2)$, where x is ρ/r, and x varies between 0 and 1/4.

[m]50 years refers to about two generations of fishers and implies that intergenerational equity is sufficiently accommodated by maximizing the long-run discounted utility. The future may be protected even more with other criteria (cf. refs. 13 and 14).

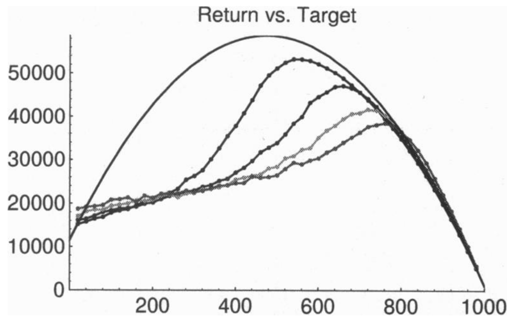

FIG. 4. Average value of fishery/savings portfolio after 50 years as a function of target stock size, starting with an initial portfolio value of \$1000, based on 1000 replicates at each target. Solid curve at top is theoretical yield in a constant environment without risk. Curves from simulation (from top to bottom) illustrate fluctuations, σ, of 0.2, 0.4, 0.6, and 0.8; average r is 1, average K is 1000, ρ is 0.05, and the time step is 1 year. The best target stock sizes for this range of σ values are about 540, 660, 720, and 760, respectively.

fluctuations of r and K (which are assumed to fluctuate together); second, the stock size estimate contains sampling error, which leads to a somewhat incorrect annual catch quota; and third, the harvest quota is imperfectly executed so that what is actually harvested differs from the specified quota. If the stock goes extinct, the portfolio continues earning solely from interest on savings. A range of targets from 0 (immediate liquidation of the stock) to K (no harvesting at all) is selected, and for each target 1000 replicates are carried out.

Fig. 4 shows the average total value of the fishery/savings portfolio after 50 years as a function of target stock size, starting with an initial portfolio value of 1000 dollars, based on 1000 replicates at each target. The solid overarching curve at the top is the theoretically expected yield from the portfolio in a constant environment without risk.[n] The best target is 475, which would permit the portfolio to increase from \$1000 to nearly \$60,000 after 50 risk-free years. This target is the economic optimum target at which the slope of the production function equals the interest rate, as outlined in Fig. 1, but using $r = 1$ rather than 0.25 in anticipation of data presented later. The curves plotted below the theoretical risk-free ideal curve represent the returns from portfolios with increasing risk. Risk is introduced through parameter σ. The r, K, stock estimate, and harvesting accuracy are chosen each year by multiplying their mean or true values by $(1 + \sigma z)$ where z is a random variable uniformly distributed between -1 and 1. If σ is 0.2, for example, then r, K, the stock estimate, and harvesting rate all fluctuate around their mean or true values by $\pm 20\%$.[o] The curves in Fig. 4 illustrate fluctuations σ of 0.2, 0.4, 0.6, and 0.8. The best target stock sizes for this range of σ values are about 540, 660, 720, and 760, respectively. This simulation shows that as the risk increases the target stock size for the best portfolio return also increases and is generally in the vicinity of $(3/4)K$.

Fig. 5 shows the risk of fishery collapse over 50 years as a function of stock size. The curve to the left is for $\sigma = 0.2$, and increasingly higher σ values follow to the right. The risk of collapse is 1 for low target sizes and drops to 0 at high target sizes. The position of the knee in the curve depends on the degree of fluctuation. With $\sigma = 0.2$, the risk of collapse is 0 if the target is about 600 or beyond, whereas if $\sigma = 0.8$ the target must exceed $\approx$900 for the risk of collapse nearly equal to 0.

[n]The portfolio's value in a risk-free environment at time t in $(0, \tau, 2\tau, 3\tau, \ldots)$ for a target stock of N is $v_t = N_t + (rN(K - N)/K)((1 + \rho\tau)^t - 1)/\rho + (K - N)(1 + \rho\tau)^t$. The time step τ is 1 year.

[o]At each time step in the simulation, $r_t = (1 + \sigma_{rK}z')r$, $K_t = (1 + \sigma_{rK}z')K$, $N_{\text{est}} = (1 + \sigma_{Nt}z'')N_{t-\tau}$, $\text{TAC} = F_{\text{o}}N_{\text{est}}\tau$, $h_t = (1 + \sigma_h z''')\text{TAC}/\tau$, and $N_{t+\tau} = \int_t^{t+\tau} = (dN/dt - h_t)dt$. The target fishing mortality F_{o} is found from the target stock N_{o} as $r(K - N_{\text{o}})/K$. The three σ values were set equal to a common value.

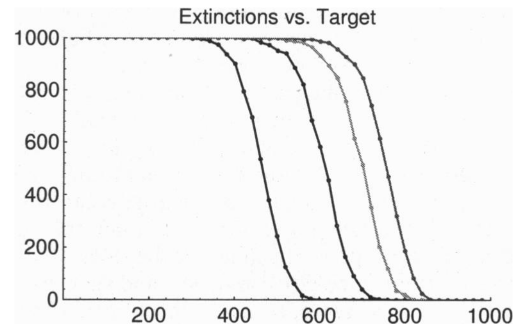

FIG. 5. Risk of fishery collapse over 50 years, measured as the number of simulations where the stock became extinct, as a function of stock size. Curves from left to right are for σ of 0.2, 0.4, 0.6, and 0.8.

These simulations demonstrate that natural insurance is worth buying. By foregoing maximum short-term earnings and managing for a target of $\approx(3/4)K$ instead, long-term profit is maximized.[p]

Implementation

The policy goal is to ensure that fishers harvest only when the stock size lies to the right of the peak in the production curve where stability occurs. This aim can be fulfilled in two ways. Currently, most fisheries use a command-and-control approach whereby annual fishing quotas drop to 0 as the stock size falls below the target level. This system could also be used to maintain a target of $(3/4)K$ rather than the targets previously set. Alternatively, policies can be devised that make short-term profit maximization coincide with long-term profit maximization. Market forces will then lead to a stable fishery because it will be uneconomical in the short term to fish when the stock is below target.

A market-based policy to maintain the stock at a stable size must ensure that the price per fish received by a fishery (termed adjusted price, P_a) is low when the stock is depressed and approaches market value when the stock is robust. In this policy context, the fishery has a financial incentive to protect the stock. The adjusted price may be controlled by taxing the fish at dockside according to the stock size at the time of harvest. For example, if it is decided to adjust the price using a dockside tax, no tax is paid when the stock is at the desired level of $(3/4)K$. The tax is paid only when harvests are taken from a stock that is below $(3/4)K$. The adjusted price mechanism works because a fishery is faced with finding the optimum balance between two goals: harvesting few fish causing the stock to increase and thereby bring a higher price per fish vs. harvesting many fish causing the stock to decrease and thereby bring a lower price per fish. The adjusted price schedule is set up so that the balance between maximizing price per fish and maximizing quantity of harvest occurs when the stock is at $(3/4)K$.[q]

[p]Advantages of a high stock target have also been pointed out by Doubleday (15), although no economic costs and benefits were considered. Also, stochastic generalizations of the economic optimality criterion relating the slope of the production function to the interest rate have been derived, as reviewed by Clarke et al. (16), but the application to fishery policy is not immediate (see also refs. 17–21).

[q]The adjusted price $P_a(N)$ per fish as a function of the stock size N should satisfy $\rho = F'(N) + F(N)P'_a(N)/P_a(N)$ at $N = N_r$ to ensure that the fishery views a stock size of N_r as financially optimal. $F(N)$ is the production function for the fishery and ρ is the savings account interest rate. Suppose the adjusted price is assumed to scale exponentially with stock size $P_a(N) = ae^{bN}$. The fishery will view $N = (3/4)K$ as the financially optimal stock size if $b = 8(1 + 2\rho/r)/(3K)$ and $a = e^{-b}\mathrm{r}(3/4)K$, and the adjusted price will equal the market price when N equals $(3/4)K$. The formula that $P_{\mathrm{a}}(N)$ must satisfy at $N =$

The calculations for the adjusted price may also take into account the number of firms that are in the fishery.[r,s]

The adjusted price schedule affects both the equilibrium and dynamics of fishery management. Once the schedule is in place, ordinary short-term economic optimization favors a target of $(3/4)K$, and the optimal path to this target would involve bang-bang control, although this is presumably undesirable to implement. Instead, labor markets can provide a graded control possibly more effective than the annually adjusted catch quotas presently in use. If the stock drops below target, the adjusted price per fish drops, and then the money spent on labor will decrease, resulting in a lowered harvesting effort. Regulating by constant effort is stabilizing by itself and, if the effort itself also drops when the stock is below target, the result is even more stabilizing.

Application: Newfoundland

With the spectacular collapse of one of the world's most productive fisheries, Newfoundland fishing fleets are now idle while stocks of cod and other groundfish recover. The Canadian Department of Fisheries and Oceans (DFO) is now aiming "to create an Atlantic groundfish fishery that is ecologically and commercially sustainable" (22). In this section, we illustrate how the theory presented above would be applied to achieve this aim.

The parameters that must be determined are the stock's intrinsic rate of increase r; the stock's carrying capacity K; the price per unit stock P; and interest rate ρ. For Newfoundland cod, r is ≈ 1 per year (annual percentage of 100% compounded continuously), K is ≈ 1.4 million tons, and P is $\approx$C\$550 per ton. The interest rate ρ is taken at 0.05 per year (annual percentage of 5% compounded continuously). These parameters are shown in Fig. 6.[t]

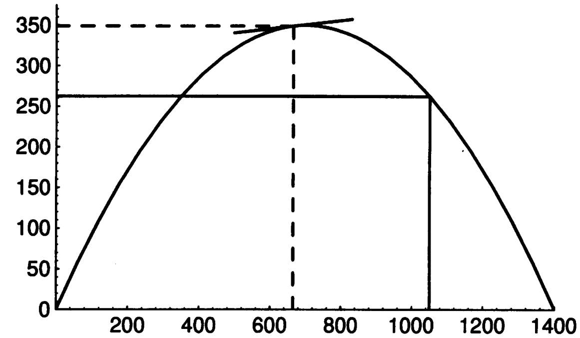

FIG. 6. Setup for managing the Newfoundland cod fishery. The r is 1 per year, K is 1400 thousand tons, and ρ is 0.05. The economic optimum stock shown with a dashed line. Ecologically recommended stock shown with a solid line.

The economically optimal stock N_o is 665,000 tons,[u] whose market value is C\$366 million. This stock supports a steady state annual harvest of 349,000 tons, worth C\$192 million. The capital value of this fishery is C\$3.84 billion—i.e., an investment this large would be needed to earn C\$192 million annually at an interest rate of 0.05. The capital value of the fishery greatly exceeds the market value of the stock because the productivity of the fishery is much higher than the interest rate.

The ecologically recommended stock size is 1,050,000 tons of fish, which supports an annual harvest of 263,000 tons worth C\$144 million. If this target is maintained with annually adjusted total allowable catches (TACs), then the target fishing mortality is 0.25 (i.e., $r/4$).

The cost of operating the fishery at an ecologically stable equilibrium is the annual interest foregone by leaving in the stock the additional 385,000 tons of fish, whose market value is C\$212 million, and which would earn C\$10.6 million annually in interest, plus the difference between the economically optimal and ecologically recommended harvest rates, which is 87,000 tons, worth C\$47.6 million annually. This cost is $\approx 1.7\%$ of the capital value of the fishery, which may be inexpensive given the magnitude of the insured amount and the near certain risk of liquidating the fishery by overfishing.

A schedule of adjusted prices that makes a stock of 1,050,000 tons the financially optimum stock size is $P_a(N) = ae^{bN}$, where $a = 0.111$ and $b = 3.81 \times 10^{-9}$. In particular, $P_a(3K/4) = 1.00$, $P_a(K/2) = 0.48$ and $P_a(K/4) = 0.23$. Thus, if the stock should drop to 350,000 tons, a fish harvested at that time would bring only \$0.23 per dollar of market value. Fishing would certainly be unprofitable under these conditions. The best balance of high price and high harvest would occur at a stock size of 1,050,000 tons, and fish harvested at would bring full market value.

If the fishery, as a commons, were organized into more than one competing firm, the adjusted price would vary more steeply with stock size because the incentives to reduce harvest at low stock sizes would need to be greater to counteract the combined effect of firms acting individually to maximize revenue.

N_r is derived as follows. We wish the h that maximizes $\int_0^\infty e^{-\rho t}P_a(N)h(t)dt$. First, form the Hamiltonian, $\mathcal{H} = P_a h + \lambda(F - h)$. Then, from $\partial\mathcal{H}/\partial h = 0$, at equilibrium, we have $\lambda = P_a$. Also, $d\lambda/dt = -\partial\mathcal{H}/\partial N + \rho\lambda = \lambda(P - F') - hP_a'$, and $dN/dt = F - h$. Combining and rearranging these equations yields the formula, $\rho = F'(N) + F(N)P_a'(N)/P_a(N)$. As is, this formula predicts the financially optimal stock size given ρ, $P_a(N)$ and $F(N)$. If price does not depend on stock size, $P_a'(N) = 0$, and the formula reduces to the familiar $\rho = F'(N)$. However, we stipulate that the financially optimal stock size shall be N_r, so this equation can be used instead to determine the properties P_a should have so that the financially optimal stock size works out to coincide with the ecologically recommended stock size.

[r]The economically optimal stock size as seen by each firm, with M firms, is $N_o(M) = (K/2)(1 - M\rho/r)$. The harvest per firm at this stock size is $h_o(M) = rK(1 - (M\rho/r)^2)/4$. So the aggregate harvest from the M firms is $Mh_o(M)$, which decreases monotonically with M.

[s]Again suppose the adjusted price scales exponentially with stock size, $P_a(N) = ae^{bN}$. If $b = 8(1 + 2M\rho/r)/(3K)$ and $a = e^{-br}(3/4)K$, then each of the M firms views a stock size of $(3/4)K$ as financially optimal from its own standpoint, and each will obtain full market value per fish when the stock equals $(3/4)K$.

[t]The Newfoundland fishery is considered here to include Northwest Atlantic Fisheries Organization divisions 2J, 3K, 3L, 3N, 3O, 3Ps, 3Pn, and 4R that together comprise $\approx$550,000 km^2 surrounding Newfoundland and lying off the coast of Labrador out to the 200-mi limit. Fig. 1 presents the biomass estimates and landings specifically for the divisions 2J, 3K, and 3L, which comprise $\approx$400,000 km^2. The maximum yearly increase in stock for these three divisions combined is $\approx$3-fold (cf. 1985–1986). Within these divisions the maximum yearly increase is also $\approx$3-fold (3.3 in 2J from 1985 to 1986, 3.7 in 3K from 1985 to 1986, 3.6 in 3K from 1988 to 1989, 2.8 in 3L from 1989 to 1990). Therefore, $r = \ln(3) \approx 1$. Because the harvest and stock appear to be at equilibrium from 1981 to 1990, K can be back-calculated from the known r, harvest, and stock. Solving for K in $h = rN(K - N)/K$ yields $K = rN^2/(rN - h)$. From inspection of Fig. 1, h is $\approx$250,000 tons per year during 1981–1990, and the stock N is $\approx$500,000 tons during this period. Hence, K for this region works out to be $\approx$1,000,000 tons. Within this region, the harvest appears to equal the MSY ($rK/4$ = 250,000). Because these divisions together comprise $\approx$400,000 km^2, the carrying capacity is $\approx$2.5 tons per km^2, and therefore $K \approx$ 1,400,000 tons of cod for the entire Newfoundland fishery of 550,000 km^2. The price per ton, P, in 1991 Canadian dollars has varied between about C\$450 in 1985 to about C\$620 in 1991, averaging about C\$550 per ton.

[u]This value is $(K/2)(1 - \rho/r)$. If costs that vary with stock size are taken into account, the economically optimal stock is slightly higher, 668,000 tons. The coefficient c for stock-size-dependent costs is 3700, based on a market price P of C\$550 per ton; price per boat year E of C\$1000; and catchability q of 0.0005 annually (based on data in refs. 23 and 24). The c would have to be 63,700—i.e., $\approx$17 times higher than it is—for the economically optimal stock to lie to the right of $K/2$. Thus, stock-size-dependent costs change the estimated optimal stock by 0.4% and can be safely ignored.

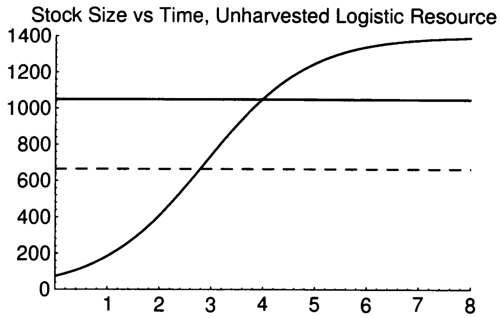

FIG. 7. Projected time course for rebuilding the Newfoundland cod stock assuming 5 years are allowed for the present stock to mature.

The harvest of 263,000 tons annually from the ecologically recommended stock is 75% of the 1981–1990 average of ≈350,000 tons (3, 25). Thus, this harvest should maintain the fishing industry (fishing and processing) at ≈3/4 of its former size, which in Newfoundland was ≈600 families with a mean income of C$25,000 (22). The maximum sustainable yield is ≈350,000 tons annually, and the harvest during 1981–1990 often exceeded this value. Therefore, the harvest levels of the past are unsustainable by any theory unless the estimates of r and K for cod are revised greatly upward. Hence, the industry must contract anyway, and by managing for ecological stability the prospects of subsequent collapses are minimized.

To bring about the ecologically stable stock size, we suggest that the moratorium on fishing be retained for 2 years beyond the 5–7 years presently envisioned (see ref. 1). The time frame of 5–7 years is based on up to 5 years for the 1993–1994 stock of ≈74,000 tons to reach spawning age, plus 1–2 years for the stock to grow to a harvestable size. As Fig. 7 shows, we calculate the stock to reach the economically optimum size in 3 years and the ecologically recommended size in 1 additional year. Therefore, allowing 5 years to reach spawning age, plus 4 years to build up to the ecologically stable size, we calculate 9 years in total of moratorium from 1993.

The moratorium exacts a large social cost, including unemployment payments to fishers and fish processing workers of over C$400 million from 1992 to 1994, and special programs,[v] budgeted at over C$2.75 billion to replace unemployment insurance from 1994 to 1999 (26). None of this would be needed, of course, had the fishery not collapsed. Although continuing the moratorium for an additional year incurs still another year of social costs, a second collapse would repeat the entire set of social costs, plus the loss of the capital value of the fishery itself, and other suffering that has not been valued monetarily. Once the fishery is regenerated with a stable stock size and harvest, these social costs disappear. Thereafter, the only remaining cost is that of operating the fishery at a configuration whose profit is less than maximal in the short term, in exchange for ecological stability—i.e., the annual cost of the natural insurance.

When the Venetian mariner John Caboto (alias John Cabot) returned to England from his discovery of Newfoundland in 1497, he related to his companion, Raimondo de Soncito, the now-legendary story about the productivity of Newfoundland's waters. As Raimondo de Soncito later wrote to the Duke of Milan ". . . the sea is covered with fishes, which are caught not only with the net but with baskets, a stone being tied to the them in order that the baskets may sink in the water" (27). Although early explorers tended to exaggerate, the extraordinary productivity of the Newfoundland cod fishery is well known and invites optimism in the long term if managed for ecological stability.

[v]Northern Cod Adjustment Recovery Program, Atlantic Groundfish Adjustment Program, Atlantic Groundfish Strategy.

Summary Recommendation

(*i*) Establish a target stock at 3/4 of the average unharvested abundance.

(*ii*) Tax the revenues from any fish caught when the stock is below target.

We thank G. Brown, L. Goulder, D. Kennedy, C. Perrings, and D. Starrett for discussions on the economic aspects of this work. We also thank many people for providing data and general information on fisheries: Bruce Anderson, Denise Blais-Saydeh, Leo Brander, Keith Brickley, Michael Brody, Leslie Burke, Jim Davis, Brian Drysdale, Ray Edwards, Joan McDougal, Joanne Morgan, Gordon Moulton, Debbie Murphy, Robert Nowak, Bob O'Boyle, Trevor Rothwell, and Doug Tilley (Canadian Department of Fisheries and Oceans); Fred Baker (Statistics Canada); Mark Holliday, Chris Kellogg, Steve Murawski, and Joan Palmer (National Marine Fisheries Service, U.S.); and Charles Cooper, Leo Erwin, Douglas Marshall, and Morton Miller (Fisheries Management Council, U.S.). We acknowledge the comments of two reviewers on an earlier draft.

1. FRCC (1993) 1994 Conservation Requirements for Atlantic Groundfish, Report to the Minister of Fisheries and Oceans (Fisheries Resource Conservation Council, Ottawa, Canada).
2. World Resources Institute (1994) *World Resources 1994-95* (Oxford University Press, Oxford).
3. NAFO (1994) Report of Scientific Council, SCS Doc.94/19 (Northwest Atlantic Fisheries Organization).
4. May, R. M. (1977) *Nature (London)* **269,** 471–477.
5. Munro, G. R. & Scott, A. D. (1985) in *Handbook of Natural Resource and Energy Economics,* ed. Kneese, A. V. & Sweeney, J. L. (North-Holland, Amsterdam), Vol. 2, pp. 623–677.
6. Conrad, J. & Clark, C. W. (1987) *Natural Resource Economics: Notes and Problems* (Cambridge University Press, Cambridge, U.K.).
7. Reed, W. J. (1974) *Math. Biosci.* **22,** 313–337.
8. Aron, J. (1979) *Math. Biosci.* **47,** 197–205.
9. Cushing, D. H. (1981) *Fisheries Biology* (The Univ. Wisconsin Press, Madison, WI), 2nd Ed.
10. Rosenberg, M. J. *et al.* (1993) *Science* **262,** 828–829.
11. May, R. M. *et al.* (1978) *Math. Biosci.* **42,** 219–252.
12. Walters, C. J. & Ludwig, D. (1981) *Can. J. Fish. Aquat. Sci.* **38,** 704–720.
13. Chichilnisky, G. & Heal, G. (1993) *J. Econ. Perspec.* **7,** 65–86.
14. Heal, G. (1993) Thesis (Columbia Business School, ●●).
15. Doubleday, W. G. (1976) *Int. Comm. Northwest Atlantic Fisheries* **1,** 141–150.
16. Clark, C. W. *et al.* (1985) in *Progress in Natural Resource Economics,* ed. Scott, A. (Clarendon Press, Oxford), pp. 99–120.
17. Beverton, R. & Holt, S. (1957) *London Fish. Invest. Ser. 2* **19,** 533.
18. Ricker, W. E. (1958) *J. Fish. Res. Bd. Canada* **15,** 991–1006.
19. Shepherd, J. G. & Horwood, J. W. (1979) *J. Cons. Int. Explor. Mer.* **38,** 318–323.
20. Ludwig, D. (1980) *J. Cons. Int. Mer.* **39,** 168–174.
21. Ludwig, D. & Hilborn, R. (1983) *Can. J. Fish. Aquat. Sci.* **40,** 559–569.
22. Cashin, R. *et al.* (1993) Charting a New Course: Towards the Fishery of the Future: Task Force on Incomes and Adjustments in the Atlantic Fishery. Department of Fisheries and Oceans, Ottawa, Canada.
23. DFO (1985–92) Costs and earnings of selected inshore and nearshore fishing enterprises in the Newfoundland region, Economic and Commercial Analysis Reports: 4, 36, 93, 113 (Department of Fisheries and Oceans, Dartmouth, NS, Canada).
24. Voutier, K. C. & Carew, K. A. (1987) Fishing effort, revenues and deployment patterns in the fisheries of the Newfoundland region, Program Coordination and Economics Branch, Newfoundland Region (Department of Fisheries and Oceans, Dartmouth, NS, Canada).
25. DFO (1994) Report on the status of groundfish stocks in the Canadian northwest Atlantic, DFO Atlantic Fisheries Stocks Status Report 94/4 (Department of Fisheries and Oceans, Dartmouth, NS, Canada).
26. Task Force Secretariat & Statistics Canada (1994) Task Force Data Compendium: Data Sources, Verification and Selected Data. Prepared for the Task Force on Incomes and Adjustment in the Atlantic Fishery (Canadian Department of Fisheries and Oceans, Ottawa, Canada).
27. Olson, J. E. & Bourne, E. G., eds. (1934) *The Northmen, Columbus and Cabot* (Barnes & Noble, New York), pp. 985–1503.